A SURVEY OF DYNAMIC SPECTRUM ACCESS:
SIGNAL PROCESSING AND NETWORKING PERSPECTIVES

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ABSTRACT

In this paper, we provide a survey of dynamic spectrum access techniques. Various approaches envisioned for dynamic spectrum access are broadly categorized under three models: dynamic exclusive use model, open sharing model, and hierarchical access model. Based on this taxonomy, we provide an overview of the technical challenges and recent advances under each model.

Index Terms: Dynamic spectrum access, spectrum property rights, spectrum commons, spectrum underlay, spectrum overlay, opportunistic spectrum access.

1. INTRODUCTION

The underutilization of the radio spectrum as revealed by extensive measurements of actual spectrum usage [1] has stimulated exciting activities in the engineering, economics, and regulation communities in searching for better spectrum management policies. The diversity of the envisioned spectrum reform ideas is manifested in the number of technical terms coined so far: dynamic spectrum access vs. dynamic spectrum allocation, spectrum property rights vs. spectrum commons, opportunistic spectrum access vs. spectrum pooling, spectrum underlay vs. spectrum overlay. Often, the broad term "cognitive radio" is used as a synonym for dynamic spectrum access. As an initial attempt at unifying the terminology and documenting recent developments, we provide a taxonomy of dynamic spectrum access and an overview of the technical challenges and advances in this emerging research area.

2. A TAXONOMY

2.1. Dynamic Spectrum Access

Standing for the opposite of the current static spectrum management policy, the term "dynamic spectrum access" has broad connotations that encompass various approaches to spectrum reform. The diverse ideas presented at the first *IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN)* [2] suggest the extent of this term. As illustrated in Figure 1, dynamic spectrum access strategies can be generally categorized under three models.

Dynamic Exclusive Use Model   This model maintains the basic structure of the current spectrum regulation policy: spectrum bands

are licensed to services for exclusive use. The main idea is to introduce flexibility to improve spectrum efficiency. Two approaches have been proposed under this model: *spectrum property rights* [3,4] and *dynamic spectrum allocation* [5]. The former approach allows licensees to sell and trade spectrum and to freely choose technology. Economy and market will thus play a more important role in driving toward the most profitable use of this limited resource. Note that even though licensees have the right to lease or share the spectrum for profit, such sharing is not mandated by the regulation policy.

The other approach, dynamic spectrum allocation, was brought forth by the European DRiVE project [5]. It aims to improve spectrum efficiency through dynamic spectrum assignment by exploiting the spatial and temporal traffic statistics of different services. Similar to the current static spectrum allotment policy, such strategies allocate, at a given time and region, a portion of the spectrum to a radio access network for its exclusive use. This allocation, however, varies at a much faster scale than the current policy.

Based on an exclusive-use model, these approaches cannot eliminate white space in the spectrum resulting from the bursty nature of wireless traffic.
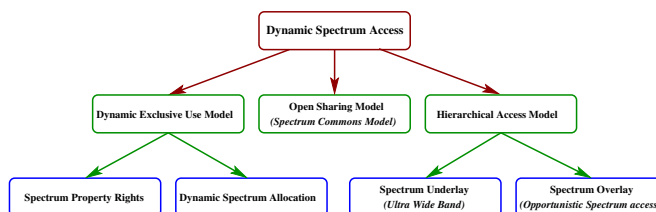

Fig. 1. A taxonomy of dynamic spectrum access

Open Sharing Model   Also referred to as spectrum commons [6,7], this model employs open sharing among peer users as the basis for managing a spectral region. Advocates of this model draw support from the phenomenal success of wireless services operating in the unlicensed ISM band (*e.g.,* WiFi). Centralized [8, 9] and distributed [10–12] spectrum sharing strategies have been initially investigated to address technological challenges under this model.

Hierarchical Access Model   Built upon a hierarchical access structure with primary and secondary users, this model can be considered as a hybrid of the above two. The basic idea is to open licensed spectrum to secondary users and limit the interference perceived by primary users (licensees). Two approaches to spectrum sharing between primary and secondary users have been considered: *spectrum underlay* and *spectrum overlay*.

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The underlay approach imposes severe constraints on the transmission power of secondary users so that they operate below the noise floor of primary users. By spreading transmitted signals over a wide frequency band (UWB), secondary users can potentially achieve short-range high data rate with extremely low transmission power. Based on a worst-case assumption that primary users transmit all the time, this approach does not rely on detection and exploitation of spectrum white space.

Spectrum overlay was first envisioned by Mitola [13] under the term "spectrum pooling" and later investigated by the DARPA XG program [14] under the term "opportunistic spectrum access (OSA)". Differing from spectrum underlay, this approach does not necessarily impose severe restrictions on the transmission power of secondary users, but rather on when and where they may transmit. It directly targets spatial and temporal spectrum white space by allowing secondary users to identify and exploit local and instantaneous spectrum availability in a nonintrusive manner.

Compared to the dynamic exclusive use and open sharing models, this hierarchical model is perhaps the most compatible with the current spectrum management policies and legacy wireless systems. Furthermore, the underlay and overlay approaches can be employed simultaneously to further improve spectrum efficiency.

We point out that the hierarchical access model is sometimes categorized under the open sharing model (see, for example, [7]). Spectrum sharing between primary and secondary users is, however, fundamentally different from spectrum sharing among peer users in both technical and regulatory aspects. We have thus separated the hierarchical access model from the open sharing model in the above taxonomy.

2.2. Cognitive Radio

The terms "software-defined radio" and "cognitive radio" were promoted by Mitola in 1991 and 1998, respectively. Software-defined radio, sometimes shortened to software radio, is generally a multi-band radio that supports multiple air interfaces and protocols and is reconfigurable through software run on DSP or general-purpose microprocessers [15]. Cognitive radio, built upon a software radio platform, is a context-aware intelligent radio capable of autonomous reconfiguration by learning from and adapting to the communication environment [16]. While dynamic spectrum access is certainly an important application of cognitive radio, cognitive radio represents a much broader paradigm where many aspects of communication systems can be improved via cognition.

3. DYNAMIC EXCLUSIVE USE MODEL

3.1. Spectrum Property Rights

The concept of spectrum property rights was first envisioned by Ronald Coase in his seminal paper published in 1959 [3], which marks the beginning of a series of successor studies and reform initiatives. An excellent exposition of challenges and existing work in defining spectrum property rights can be found in [4].

As proposed by Arthur De Vany [17] and Lawrence White [18], three parameters—time, geographic area, and spectrum band—are used to specify spectrum property rights. Specifically, "the property right would be expressed as the right to transmit over the specified spectrum band, so long as the signals do not exceed a specified strength beyond the specified geographic boundaries during the specified time period" [18]. One of the major difficulties in enforcing such spectrum property rights lies in the unpredictability of radio wave propagation in both frequency and space. Spectral and spatial

spillover is inevitable, unpredictable, and depending on the characteristics of both transmitters (potential trespassers) and receivers (property right owners). Should the spillover level at the geographic boundary of the property right be measured or computed using an agreed upon propagation model? If the former, what is to be measured (peak or average power), over which time period of the day, and at what antenna height? If the latter, how complex a model is necessary? Should the cost of suppressing adjacent channel interference be on the transmitters of one property right owner or the receivers of another property right owner? As articulated in [4], rights to spectrum cannot be "clearly defined and readily enforced as their real property counterparts." Here lies the major challenge in this approach to spectrum reform.

3.2. Dynamic Spectrum Allocation

Dynamic spectrum allocation mainly focuses on long-term commercial applications such as UMTS and DVB-T. By exploiting temporal and spatial traffic statistics, dynamic spectrum allocation aims to improve spectrum efficiency through time- and space-dependent spectrum sharing among coexisting radio services. For example, the amount of spectrum allocated to UMTS and DVB-T can vary over region and the-time-of-day.

Literature on dynamic spectrum allocation is extensive [5, 19–27]. The European DRiVE project [5] focuses on dynamic spectrum allocation in heterogeneous networks by assuming a (logical) common coordination channel. A simulation study of the impact of load prediction based on load history and simple regression schemes is reported in [28]. Regulatory aspects and issues in dynamic spectrum allocation across multiple networks are discussed in [19]. Two centralized dynamic spectrum allocation protocols that rely on a super base-station are described in [22] and their performance evaluated via simulations.

4. OPEN SHARING MODEL

There is a growing body of literature on efficient spectrum sharing among interfering peer users. Compared to the other two models, many technical issues under this model are perhaps the closest to the conventional medium access control problems. In [8, 9, 29], centralized spectrum sharing protocols with a central coordinator (referred to as a spectrum server) are proposed. Distributed spectrum sharing and power control are studied in [10–12, 30]. Interestingly, game theory, powerful for handling selfish and noncooperative users, has found its application here as discussed in [9–11, 30].

5. HIERARCHICAL ACCESS MODEL

5.1. Spectrum Underlay

In an *underlay system*, regulated spectral masks impose stringent limits on radiated power as a function of frequency, and perhaps location. Radios coexist in the same band with primary licensees, but are regulated to cause interference below prescribed limits. For example, a low-powered radio could coexist in the same frequency channel with a high-powered broadcast radio. Because of the power limitation, underlay radios (UR) must spread their signals across large bandwidths, and/or operate at relatively low rates. An example of this is the UWB radio. The power limitation results in a corresponding limit on rate-range capabilities. An advantage of such a system is that radios can be dumb—they do not need to sense the channel in order to defer to primary users. The underlying principle is that the primary users are either sufficiently narrow-band, or

sufficiently high-powered, or the URs are sufficiently fast frequency hopping with relatively narrow bandwidth usage in each dwell, so that there is little interference from the URs.

To spread signal over a large bandwidth, URs can use spread spectrum signalling, wideband OFDM, or impulse radio. Because of the large front-end bandwidth, URs are susceptible to interference from a variety of co-existing sources, including relatively narrow-band signals from primary users. This can cause saturation of the AGC circuit leading to signal distortion and loss of dynamic range. Suppressing strong primary signals through front-end notch filters is complex, since there could be many primary signals, and not always at the same frequency locations [31, 32]. Receiver arrays can help notch some primary users by exploiting the spatial degrees of freedom.

A second problem is that high-resolution high-rate ADC is extremely challenging due to both the high power consumption of such devices and fundamental limits imposed by the noise floor [33]. Consequently, it may be necessary to devise and implement analog or digital correlators to achieve high-fidelity sampling at a rate slower than the system bandwidth.

URs must also be capable of dealing with the large delay spread and frequency selectivity of the channel. Current URs—as typified by UWB radios—tend to have limited range and rate and have largely been confined to indoor applications.

An issue that has yet to be resolved here is that of aggregate interference. Modeling of aggregate interference from URs and devising algorithms to cope with it at the primary receivers have not been adequately addressed. Another aspect of aggregate interference is that spectral masks may have to be adapted to secondary traffic load.

An UR could sense the spectrum so as to shape its transmission signal to avoid congested bands. This requires reliable sensing of the spectrum similar to the spectrum overlay systems discussed in Section 5.2. The signal is potentially weak, and the integration time can be small, since the radio must be agile. The design of such sensors is an interesting issue, and cannot be decoupled from the spectrum access issue [34, 35], and the associated costs and rewards [36]. Typical choices include low-complexity energy detectors, but they tend to perform poorly at low SNRs. Matched filter detectors are often infeasible, since an array of matched filters, each matched to a specific primary user, must be available, and the pulse shape of each primary signal must be known. Feature detectors such as cyclostationary detectors may offer some advantage since they exploit signal structure without making too many assumptions.

In summary, URs tend to be complex in terms of hardware implementation, but relatively dumb in terms of spectrum sensing and access protocols. Challenges exist in hardware implementation, front-end interference suppression, high-fidelity low-power high-rate ADC circuit design, and estimation and equalization of long delay-spread channels.

5.2. Spectrum Overlay

Spectrum overlay, or opportunistic spectrum access (OSA), can be applied in either temporal or spatial domain [37]. In the former, secondary users aim to exploit temporal spectrum opportunities resulting from the bursty traffic of primary users. In the latter, secondary users aim to exploit frequency bands that are not used by primary users in a particular geographic area. A typical application is the reuse of certain TV-bands that are not used for TV broadcast in a particular region. In the TV broadcast system, TV-bands assigned to adjacent regions are different to avoid co-site interference. This results in unused frequency bands varying over space. In general, spectrum opportunities vary in both temporal and spatial domains.

It is often assumed in the literature that one variation is at a much slower scale than the other.

The majority of existing work on OSA focuses on the spatial domain where spectrum opportunities are considered static or slowly varying in time. As a consequence, real-time opportunity identification is not as critical a component in this class of applications, and the prevailing approach tackles network design in two separate steps: (i) opportunity identification assuming continuous full-spectrum sensing; (ii) opportunity allocation among secondary users assuming perfect knowledge of spectrum opportunities at any location over the entire spectrum. Opportunity identification in the presence of fading and noise uncertainty has been studied in [38–41]. Spatial opportunity allocation among secondary users can be found in [42–44] and references therein.

OSA in the time domain requires a joint design of spectrum sensing and access [45, 46]. Tracking the rapidly varying spectrum opportunities becomes a critical issue [47], and a simple yet sufficiently accurate statistical model of spectrum occupancy is crucial to the efficiency of spectrum opportunity tracking [48]. Errors are inevitable in real-time sensing, and the characteristics of the spectrum sensor should be taken into account in making spectrum access decisions [34, 35].

Initial attempts at addressing the identification and exploitation of temporal spectrum opportunities that also vary in space can be found in [46, 49]. For an extended overview of challenges and recent developments in OSA, readers are referred to [47].

6. CONCLUSION

The debate on spectrum reform is far from reaching a conclusion. Which spectrum reform model will prevail remains to be seen. Research efforts in the signal processing and networking communities are particularly important in providing technical data to access the potentials of each of the three models of dynamic spectrum access.

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